AD-774 391

INVESTIGATION OF DIFFUSERS FOR GAS DYNAMIC LASER NOZZLES

David G. Clawson

Air Force Institute of Technology

Prepared for:

Air Force Weapons Laboratory

December 1973

AD724391

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Air Force Institute of Technology (AFIT-EN) Wright-Patterson AFB, Ohio 45433	Unclassified
	2b. GROUP

3. REPORT TITLE

Investigation of Diffusers for Gas Dynamic Laser Nozzles

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
AFIT Thesis

5. AUTHOR(S) *(First name, middle initial, last name)*

David G. Clawson
2nd Lt.   USAF

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1973	27	7
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	GAM/ME/73A-3
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
Approved for public release; IAW AFR 190-17 JERRY C. HIX, Captain, USAF Director of Information	Air Force Weapons Laboratory Kirtland AFB, New Mexico

13. ABSTRACT

Schlieren photographs were used to analyze the flow characteristics of diffusers for a Mach 6.0 double nozzle assembly. This assembly of two nozzles, comprised of one (1) full center and two (2) half side channels, was more conducive to greater boundary layer growth than a nozzle assembly with more nozzle throats. Schlieren photographs of the air flow were in line with the laser beam's orientation to the nozzles of a Gas Dynamic Laser. Dry air at 85 F total temperature, and 120 psia total pressure was expanded with a nozzle area ratio of 66.0. Different diffuser configurations were tried to determine the diffuser throat area required to start the cavity. It was determined that the cavity would start when the ratio of diffuser throat area to channel cross-sectional area was near 0.6, which is in agreement with other studies, considering the presence of wakes in the flow. Boundary layer growth is accelerated at these high Mach numbers, limiting the distance between the nozzles and diffuser; excellent optical charity flow was obtained emerging from the nozzles and close to the channel center using a multi-element diffuser, but, deteriorates rapidly further downstream.

391

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gas Dynamic						
Nozzles						
Diffusers						
Supersonic Flow						

1a
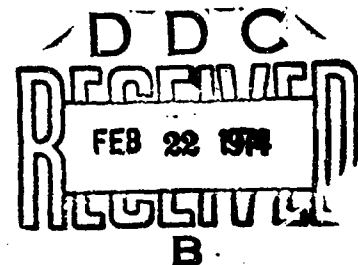
INVESTIGATION OF DIFFUSERS FOR

GAS DYNAMIC LASER NOZZLES

THESIS

GAM/ME/73A-3   David G. Clawson
             2nd Lt.   USAF

Approved for public release;
distribution unlimited.

ib

INVESTIGATION OF DIFFUSERS FOR

CAS DYNAMIC LASER NOZZLES

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

David G. Clawson   B.S.M.E.
Second Lieutenant   USAF

Graduate Aerospace Engineering

December 1973

Preface

In recent years the Gas Dynamic Laser (GDL) has been extensively subjected to theoretical and experimental analysis by the Air Force. The high beam-power output of a GDL makes the 'Death Ray' of science-fiction a reality. Increased beam power requires knowledge of the supersonic flow downstream of short multiple nozzles. The shock waves and wakes of these nozzles create a refractive index change which deteriorates the coherency of the laser beam. There is a need for information indicating the effects of boundary layers, wakes, and shocks on the flow characteristics of the supersonic gas flow. A smaller GDL can be made without heavy, high pressure combustion chambers if a supersonic diffuser is used. This study is an effort to better understand flow characteristics associated with multiple nozzles and diffusers in a GDL. Flow visualization using schlieren optical techniques will show how diffusers can improve the optical clarity of the flow.

Special appreciation and thanks are extended to the following people for their help and support of this thesis project: Dr. William Elrod, Dr. Andrew Shine, thesis advisors; John Flahive, William Baker, laboratory technicians; M. W. Wolfe, shop foreman; and Kathy Clawson my loving wife.

<div align="right">David Clawson</div>

GAM/ME/73A-3

Contents

List of Figures

List of Symbols

A_e Nozzle exit area of multiple nozzle assembly.

A_d^* Critical diffuser throat area.

A_n^* Critical nozzle throat area.

A_t Cross-sectional area of the test section.

H_n Nozzle throat height.

k Ratio of specific heats.

M_t Mach number in the test section.

P_o Stagnation pressure in the stilling chamber.

P_t Static pressure in the test section.

P_{vac} Stagnation pressure in the vacuum tanks.

S Oblique shock wave angle with respect to the horizontal.

T_o Stagnation temperature in the stilling chamber.

W Wedge angle with respect to the horizontal.

INVESTIGATION OF DIFFUSERS FOR
GAS DYNAMIC LASER NOZZLES

I. Introduction

Background

The gas dynamic laser (GDL) has been in development for approximately five years, and is schematically depicted in Fig. 1. Associated with the GDL are a number of thermodynamic flow processes that must be understood in order to predict laser performance. The flow of high-temperature combustion products (e.g., T_o = 1400 K, P_o = 17 atm) passes through a multiple nozzle array. The temperature of the gas drops to 300 K due to rapid gas expansion. This rapid drop in gas temperature causes an unstable energy balance or population inversion, which is needed to amplify the laser output power. A large array of such nozzles is necessary to allow the amount of mass flow needed to extract enough usable power from the flow. In addition, the rapid expansion requires many nozzles that are short compared to laser cavity width (Ref. 3).

The multiple nozzle concept has been considered for the construction of short supersonic wind tunnels. This concept was not used because of separation of the flow in the nozzle throats; also, the greater number of wakes and shockwaves downstream of the nozzles were detrimental for useful tests in such a wind tunnel facility (Ref. 7,1).

Problem
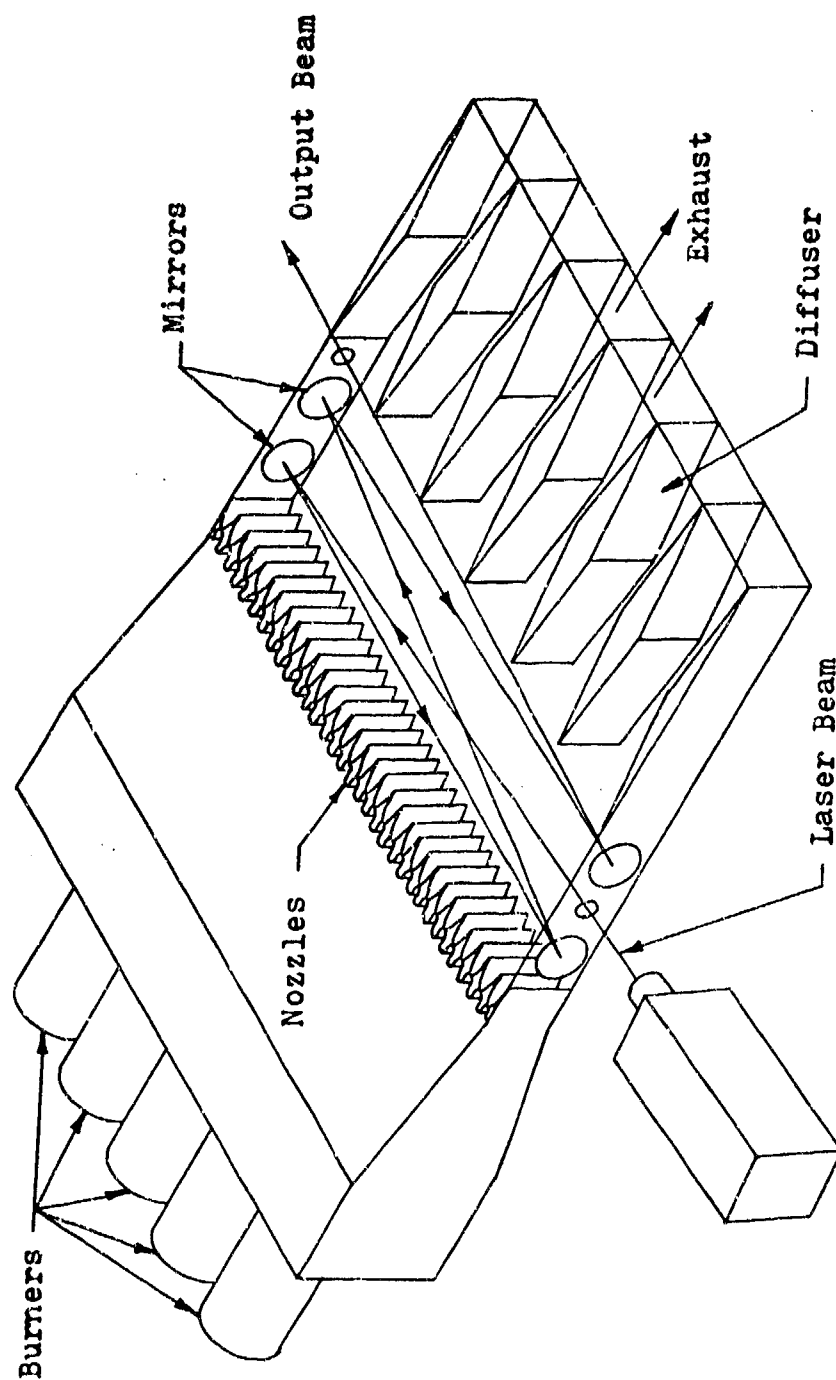
The flow quality problems, which are seperation and

Fig. 1. Schematic of a Gas Dynamic Laser.

turbulance, encountered with the wind tunnels are detrimental
to the performance of the GDL. The refraction index varia-
tion, caused by large density gradients from the shocks and
wakes in the flow downstream of the nozzles, deteriorate
the quality of the coherent laser beam. The schlieren optical
technique provides a means of investigating these variations
in the supersonic flow downstream of the nozzles.

Most GDL installations have a supersonic diffuser down-
stream of the nozzles. The diffuser increases the pressure
of the exhaust products from a low value in the cavity section
to atmospheric pressure at the exit. As a result, the diffuser
reduces the overall pressure ratio from the stagnation condi-
tion to the GDL exit for a given cavity section pressure.
The stagnation pressure chamber can be designed with smaller
high pressure stresses in the walls and flanges. For this
particular project a diffuser is a necessity in the AFIT
blow-down test facility, due to the limitation of the over-
all pressure ratio to approximately 500.

The objective of this initial investigation was to take
schlieren photographs of the supersonic flow downstream of
a nozzle assembly, which provided a means to evaluate the
optical clarity of the supersonic stream. Investigating
diffuser systems with near optimum throat area, the goal of
this study was to start a Mach 6.0 supersonic GDL model.

Scope

Test Conditions. The following test conditions were
held fixed throughout this study:

(A) The nozzle throat dimensions were held at the design value

(B) The total temperature and pressure conditions were fixed at 85 F and 120 psia

(C) The back pressure, P_{vac} was initially the highest that the vacuum pumps could obtain ($P_o/P_{vac} \doteq 500$).

Diffuser Configurations. To start this test cavity at Mach 6.0 an efficient supersonic diffuser with correct throat area must be used due to limited overall pressure ratio. Several different diffusers were tried to determine the required diffuser throat area. A more detailed analysis of the required diffuser throat area is on page 6.

Direction of View. The nozzles can be mounted horizontally to view the entire nozzle flow passage with the contour of the nozzles visible in the schlieren photographs. This position gives useful information about the flow downstream of the nozzles. Knowledge of the position of the wakes, shocks, and boundary layers is readily obtained. Other studies have extensively analyzed the view parallel to the nozzle contour (Ref. 7). Figure 2 shows what this may appear like as viewed parallel to the nozzle contour. The wakes and oblique shocks from each nozzle create a unique rhombus pattern. However, in order to minimize these sources of refractive variations, the laser beam in a GDL is usually passed perpendicular to the direction in Fig. 2. Light then passes perpendicuar to the shock waves and wakes which are now sheets extending from the nozzles. This latter approach is utilized in this study to model the actual laser.
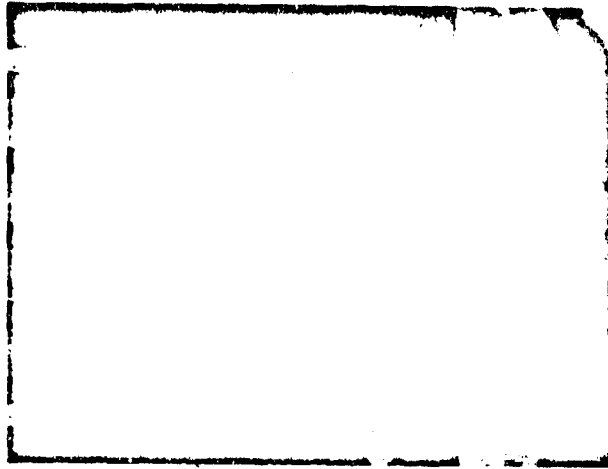
4

Fig. 2. Schlieren Photograph of Flow in a Multiple Nozzle Assembly. (Courtesy of Dr. Elrod and Dr. Shine).

Assumptions. This study is based on assumptions that are made to stay within the limitations of the facility, and as a design guide. It is assumed that air at 300 K total temperature models the combustion products (CO_2, N_2, and H_2O) of the GDL at 1400 K. The flow characteristics, with regards to wakes and shocks, are assumed similar in the GDL and this test model.

To design the supersonic diffusers, the flow is assumed to be isentropic except for shocks; also, the flow through the nozzles is assumed to be isentropic.

The high Mach number expansion through the nozzles causes the static temperature of the air to drop to a low value. This temperature sould reach 50 K, which is just above the phase change point of oxygen; a better margin is provided in the case of nitrogen. However, it is assumed that the air is still a perfect gas, with constant specific heats, and k = 1.4.

II. Diffuser Design

Initially a three-shock, supersonic diffuser, designed for maximum total pressure recovery (Ref. 4:215-22) was tried. Hermann shows which wedge angles are best to minimize total pressure loss. The three-shock diffuser was chosen because the static pressure at the diffuser exit would be closer to atmospheric pressure. In Ref. 2:578-9 there are charts, which may be used to evaluate the total pressure ratio across this three-shock system.

The total diffuser throat are was calculated by assuming the worst condition for starting. To start the flow in the cavity section, the diffuser throat must be large enough to accommodate the stagnation pressure loss of a Mach 6.0 normal shock. It can be shown (Ref. 2:95) that the total pressure loss is related to the minimum test cross-sectional areas in the following way:

$$\frac{P_{vac}}{P_o} = \frac{A_n^*}{A_d^*} \tag{1}$$

From the normal shock tables the area of the diffuser throat must be at least

$$A_d^* = 33.73 \ A_n^* \tag{2}$$

Additional diffuser throat area must be provided because of a large boundary layer. An additional 10% was assumed. Figure 3 shows a drawing of the test section. Changing the diffuser throat area while flow existed was accomplished by translating the diffuser plug by the threaded screw. The cavity could not be started with this diffuer.

6

To start the test cavity, both references 5 and 6 indicated that the center-plug diffuser has poor performance; while, the diffuser with extensions from the wall seemed to be better. This initiated the idea of using different diffuser configurations in an attempt to find what would start the test cavity. Wedges made of plexiglass 0.79 inches wide were cut with various shapes. A gasket made of a matrix of cork and rubber was just thick enough to make the wedges the same width as the channel (0.852 in.) allowing for some compression to keep the wedges from moving.

The concept of multiple nozzles was extended to diffuser design. Using simple wall extensions, plus centerbody arrangements, the diffuser system was short compared with wall-type diffusers. The centerbody served as an indicator of the Mach number at the channel centerline.
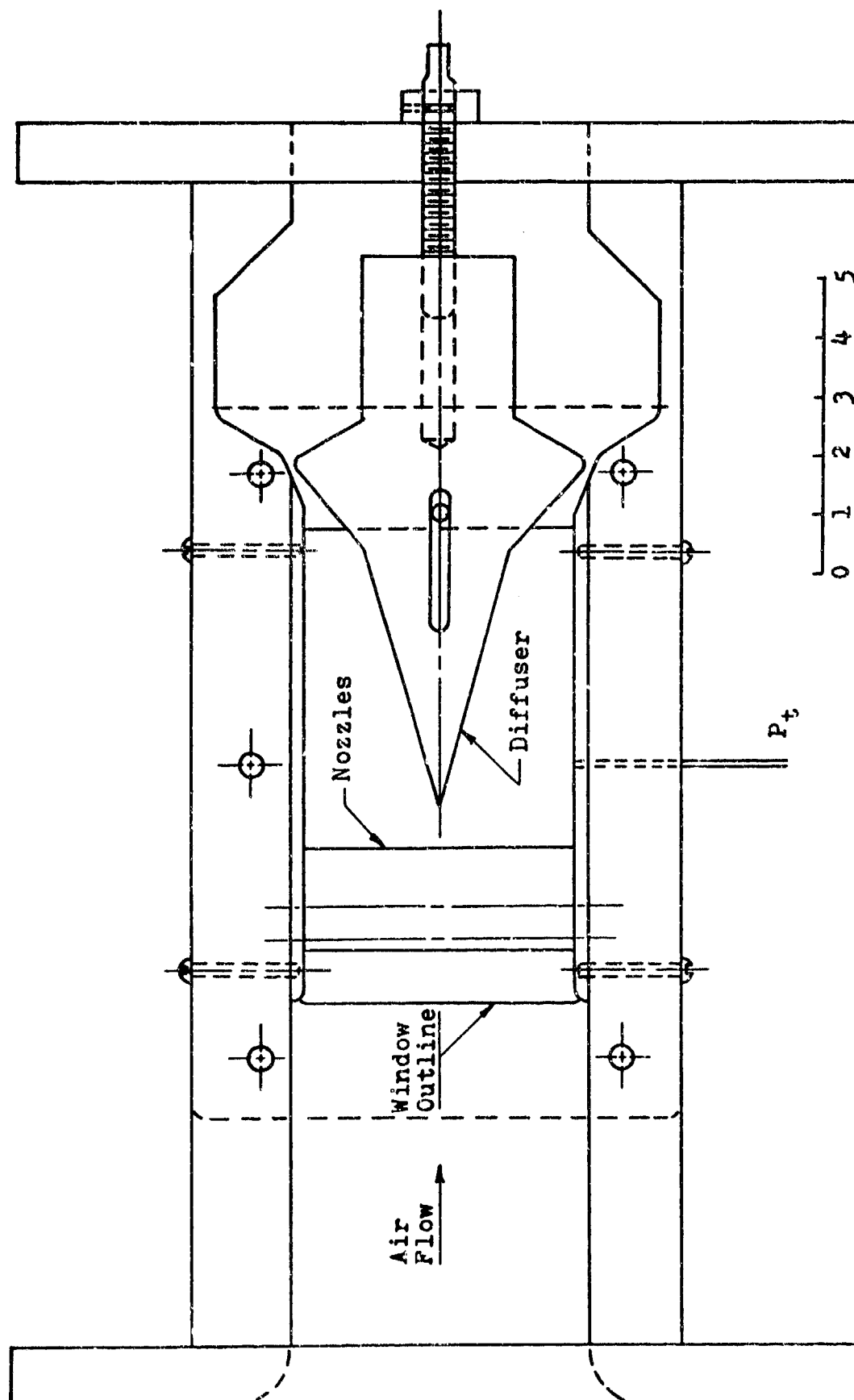
Fig. 3. Detail of Test Section.

Scale: Inches

0 1 2 3 4 5

Nozzles

Diffuser

P_t

Window
Outline

Air
Flow

III. Apparatus

The facility used throughout this study was the AFIT supersonic blow-down wind tunnel. Pressure gage instrumentation, which is described later, and the schlieren system was the supporting equipment. Figure 4, below, is a schematic of the test facility.
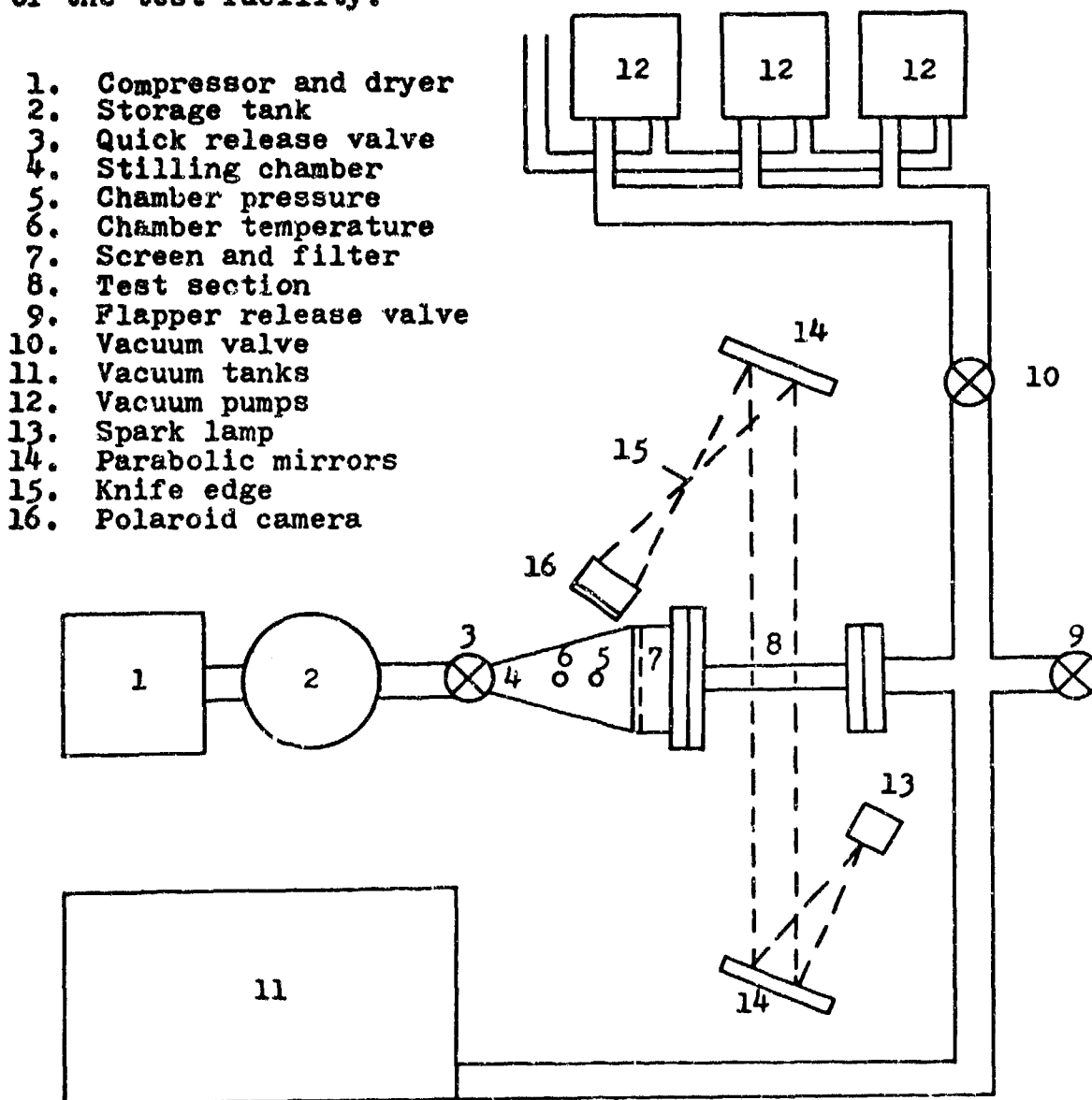
1. Compressor and dryer
2. Storage tank
3. Quick release valve
4. Stilling chamber
5. Chamber pressure
6. Chamber temperature
7. Screen and filter
8. Test section
9. Flapper release valve
10. Vacuum valve
11. Vacuum tanks
12. Vacuum pumps
13. Spark lamp
14. Parabolic mirrors
15. Knife edge
16. Polaroid camera

Fig. 4. Test Facility Schematic.

Nozzles

The nozzles, which were provided by Pratt and Whitney
Aircraft Division of United Aircraft Corporation, are 4-1/2 in.
long and have a contour shown in Fig. 5. Designed to deliver
an exit Mach number of 6.0, the nozzle area ratio (A_e/A_n^*)
of 66.0 allows for boundary layer effects.

Test Section

The two dimensional test section was 0.852 in. wide, and
4-1/2 in. high. Two nozzle blocks were used and mounted with
one 0.006 in. throat center channel, and two 0.003 in. half
nozzle channels next to the window surfaces, with the window
surface being the centerline of the nozzle contour. The
nozzles were held in the proper position by two steel plates
0.812 in. wide, 1/4 in. thick, and 8-3/4 in. long. Dowel
pins extending from the nozzle blocks were fitted into two
oversized elongated slots in the steel plates. Four small
set screws were then used to tighten each pin against a center
rib in the plate. By placing shims between the center rib
and the pins, the correct nozzle throat dimension could be
set (0.006 in.).

Considerable difficulty was encountered trying to seal
high pressure leaks around the end of the nozzle blocks where
they were butted against the mounting plates. Some improve-
ment was obtained by using 0.003-in. thick paper and wax as
a gasket material.

Seals. The sealing material between the test section
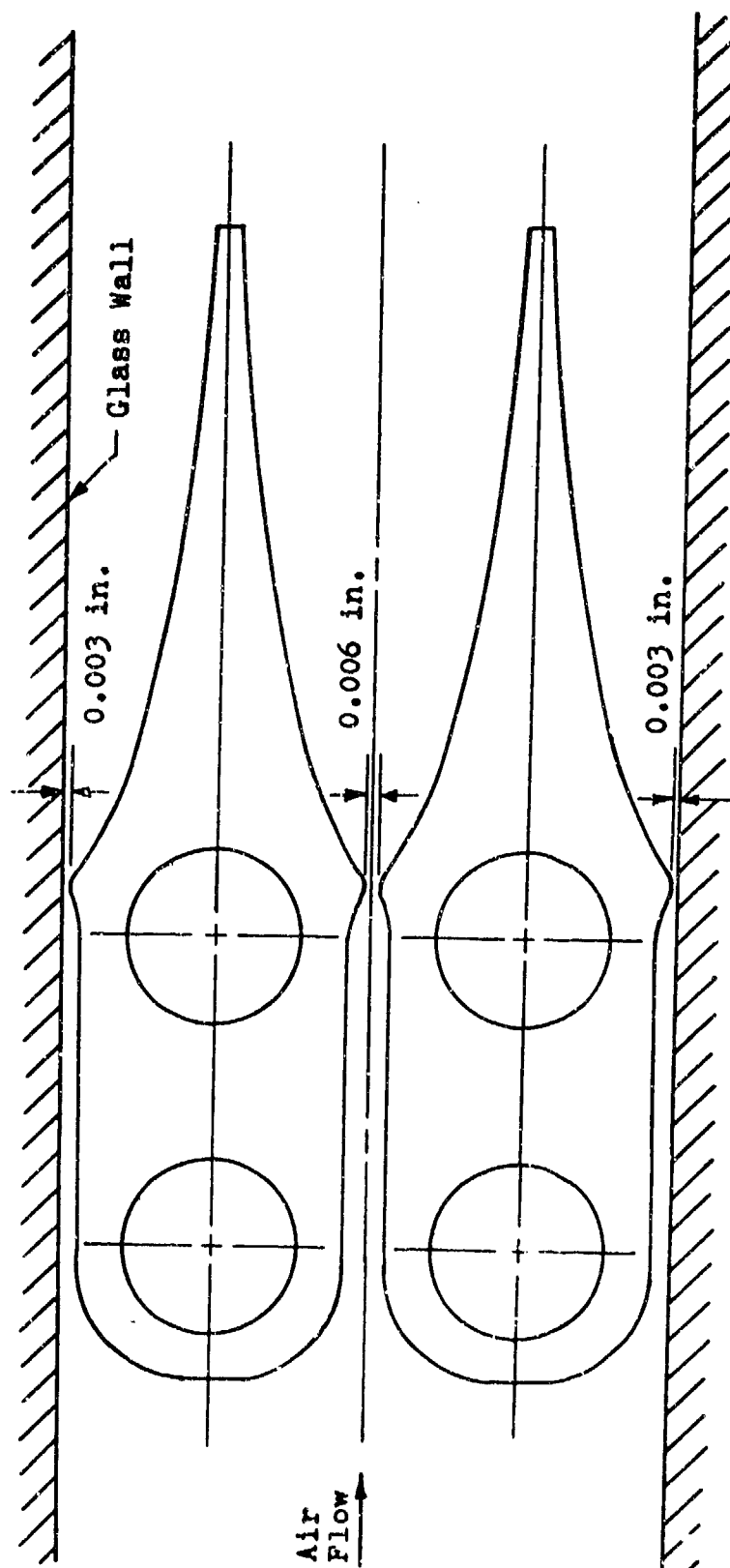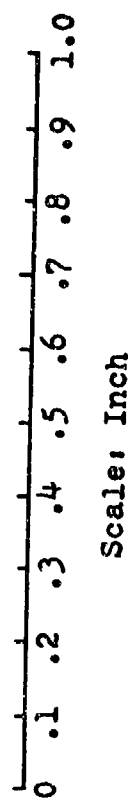assembly parts that was found to be best was hard paper

Scale: Inch

0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0

Glass Wall

0.003 in.

0.006 in.

0.003 in.

Air
Flow

Fig. 5. Two Dimensional Multiple Nozzle Contour.

11

0.020 in. thick. This was found to compress just enough to keep the window surface 0.003 in. away from the nozzles; at the same time, keeping a good tight seal. A recommendation for future projects is to use O-ring seals where close dimension tolerances must be held.

Windows. Optical glass windows provided a viewing area of 4-1/2 in. by 8 in. The glass surface was made flush with the inside walls by using a liquid-rubber epoxy which cured to a hard rubber type seal.

Schlieren System

A schematic of how the schlieren system was set up is shown in Fig. 4. This was a folded type system using either a spark lamp with approximately 1/2 microsecond duration, or a steady zirconium lamp as the light source. In all of the pictures obtained showing shocks, the knife edge was in the vertical position. Polaroid Land film, type 57, was used for photographs when using the spark lamp.

Instrumentation

The total pressure was measured on a 0-200 psig dial gage. The total temperature was indicated by a mercury bulb thermometer. Both the back pressure and the chamber static pressure were measured with 100 in. U-tube type mercury manometers.

The chamber static pressure probe was a brass tube 1/32 in. inside diameter. The tube was inserted into the test cavity until the tube's open end was flush with the steel mounting plate. It was located 1-1/2 in. downstream from the nozzle trailing edge and on the test section centerline.

IV. Experimental Procedure

The desired test section configuration was obtained by securing the diffuser pieces in position, checking the proper clearance with vernier calipers. The glass windows were cleaned so that the highest quality pictures could be made. The test section was then closed and secured.

When the test section was ready, the vacuum pumps were used to establish a pressure of about 0.25 psia in the vacuum tanks. The pumps were allowed to run throughout the entire test. In all of the test runs the total pressure was 120 psia; the total temperature was 85 F as read from the instruments on the stilling chamber.

The schlieren system was made ready, and the pressure in the vacuum tanks was noted. After initating a test with a quick-release valve, a short period of time was allowed to elapse (4 to 5 sec.) for flow disturbances to minimize. The pictures were then taken, and the pressures in the test section and the vacuum tanks were recorded. The flow was then terminated by closing the quick-release valve.

V. Results and Discussion

Mach Number

Two methods were used to determine the flow Mach number. The static to total pressure ratio (P_t/P_o), was used with the isentropic functions tabulated in Ref. 1:21-39. In addition, the Mach number was determined by measuring the angle of an oblique shock and the angle of the wedge that generated that shock. Charts were used (Ref. 1:42), which gives the variation of shock wave angle with flow-deflection angle for various upstream Mach numbers.

Table I

Mach Numbers Obtained for Various Diffusers.

Method (1): P_t/P_o ratio; Method (2): Shock wave angle

Diffuser	Method (1)		Method (2)		
	P_t/P_o	M_t	W*	S*	M_t
A	0.0021	4.9	10.0	19.0	5.5
B	0.0021	4.9	13.0	22.0	4.0
C	0.0021	4.9	15.0	29.0	3.8
D	0.0021	4.9	7.5	20.0	4.0

*Angles W and S are in degrees.

For all test runs the determined Mach number was lower than the design M_t = 6.0 value. By comparing schlieren pictures of diffusers A and B with C (Fig. 6, 7, and 8), it is evident that turbulance envokes a low Mach number. In order for the cavity to start using the 30 degree wedge in diffuser C, this centerbody had to be positioned further downstream compared to diffusers A and B. In the schlieren pictures more degeneration of the flow can be seen in Fig. 8 than in
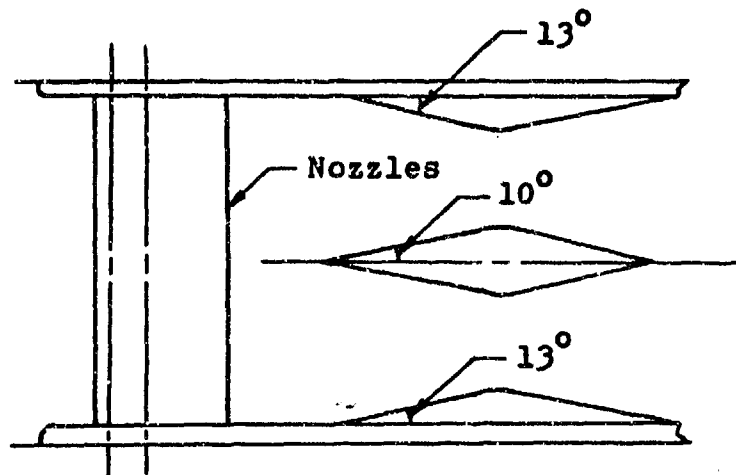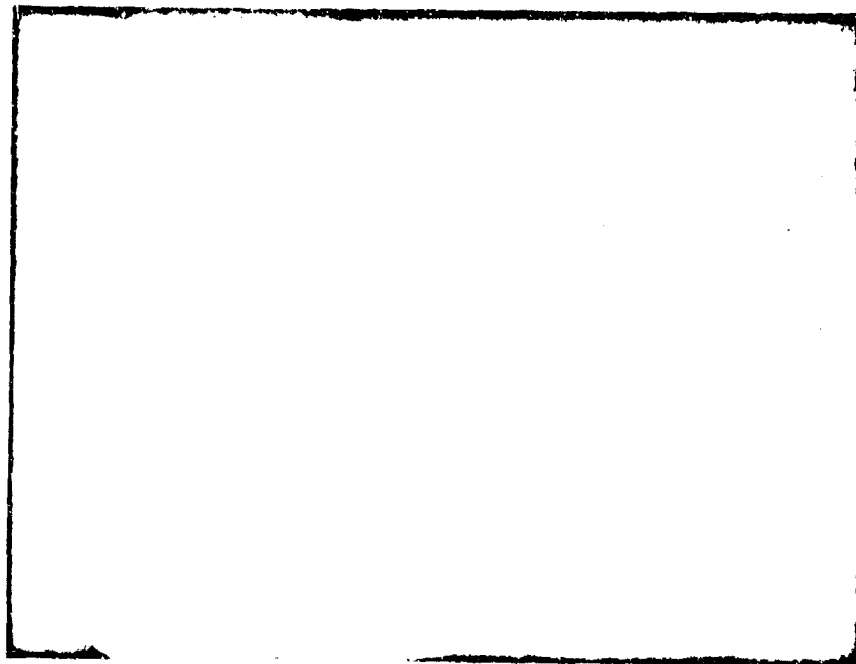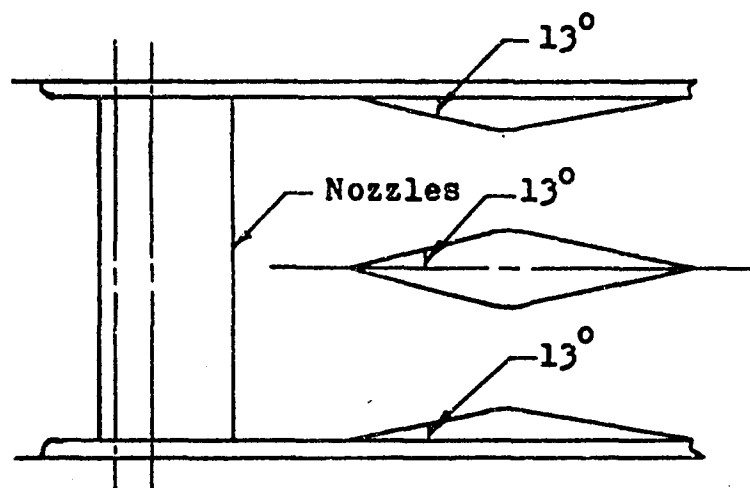
Diffuser A Schematic

Fig. 6. Schlieren Photograph of Flow
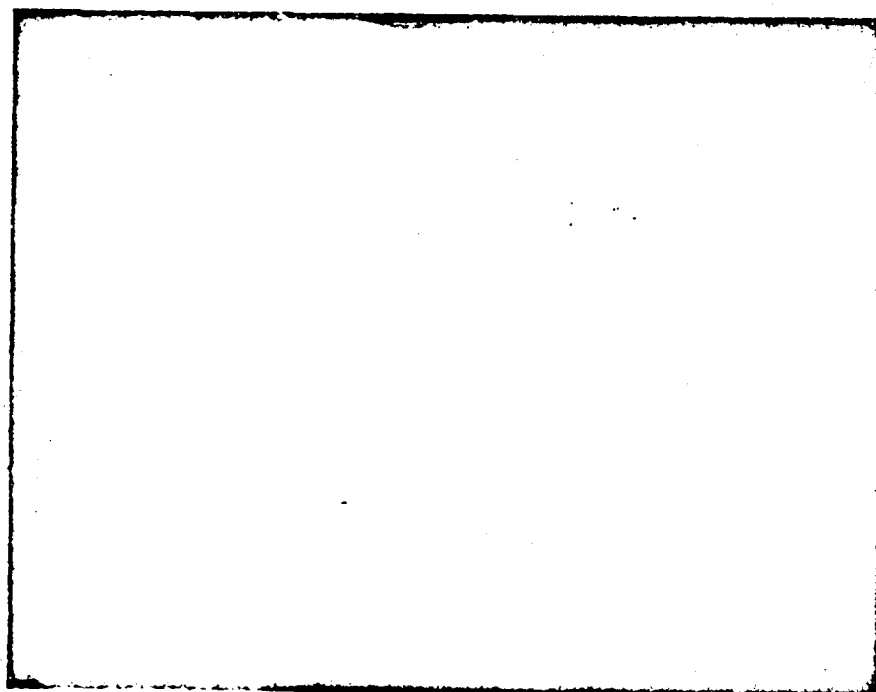Through Diffuser A, and Schematic.
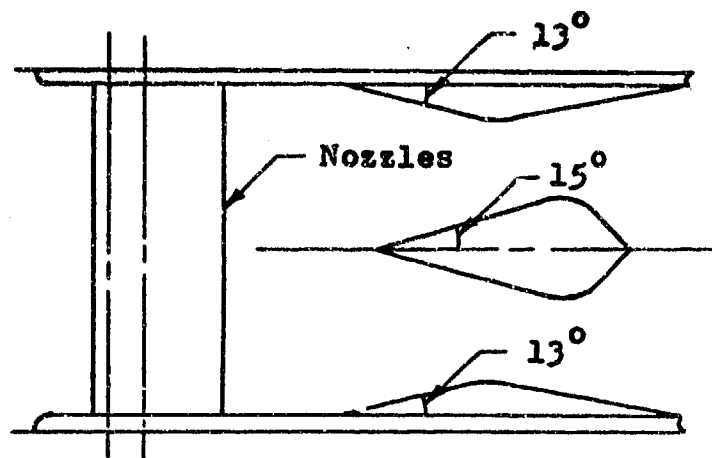
Diffuser B Schematic

Fig. 7. Schlieren Photograph of Flow
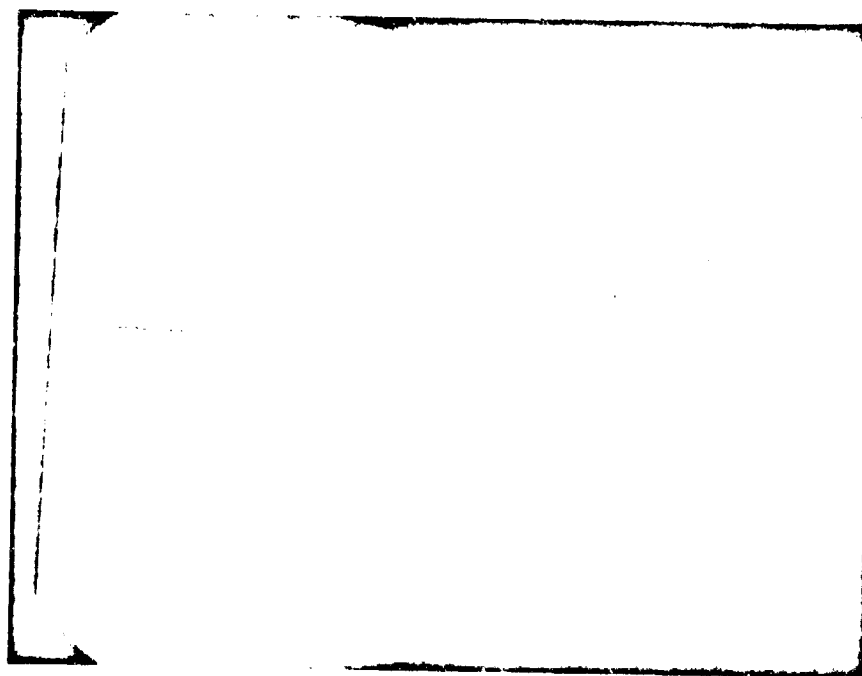Through Diffuser B, and Schematic.

Diffuser C Schematic

Fig. 8. Schlieren Photograph of Flow
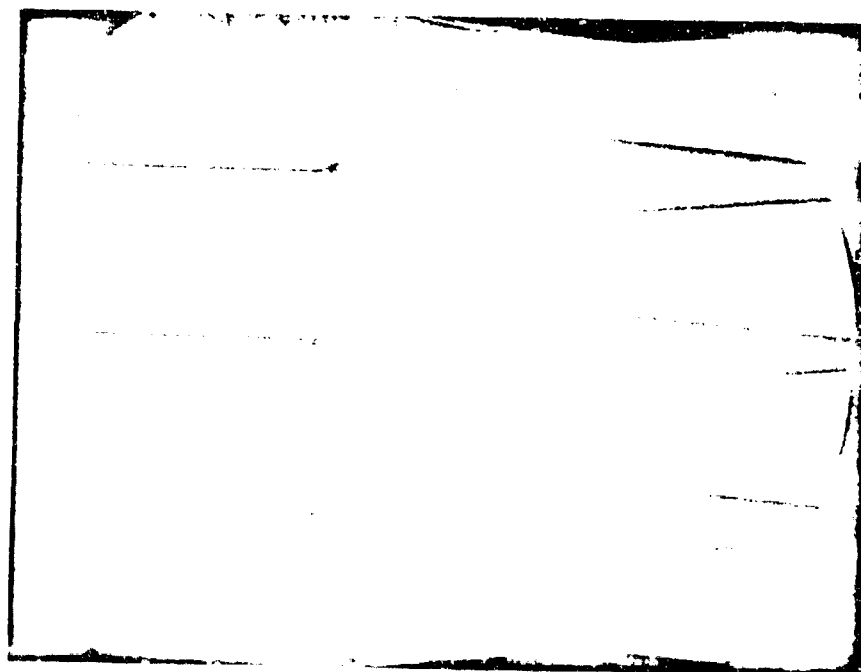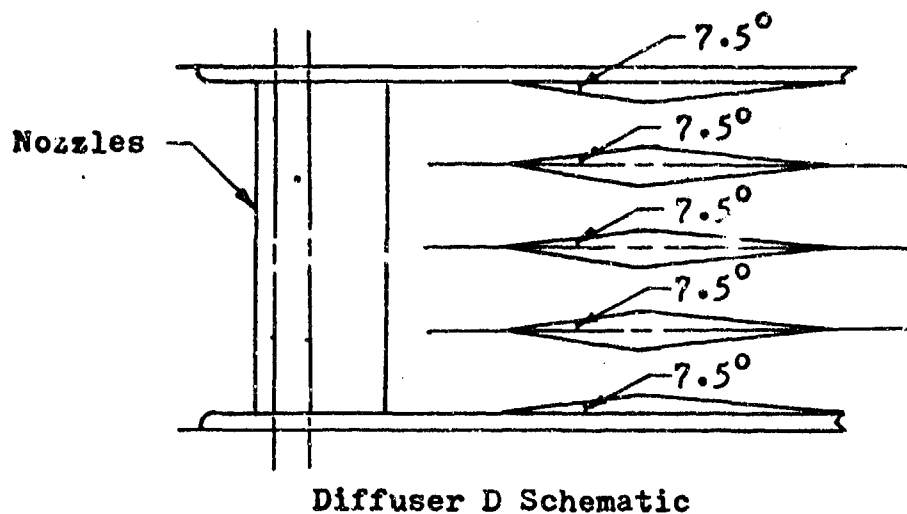Through Diffuser C, and Schematic.

17

Diffuser D Schematic

Fig. 9. Schlieren Photograph of Flow
Through Diffuser D, and Schematic.

Fig. 6 or 7. This decrease in Mach number, as a result of deterioration of the flow, was seen in other pictures also.

Figure 9 of diffuser D was a four channel design. The total throat area required to start the cavity with this diffuser was the same as other configurations investigated, in spite of the additional flow surfaces. Boundary layer control was as good if not better than the two-channel type.

In addition to the degeneration of the flow just mentioned, low Mach numbers could be a result of the nozzle throat dimension not on design (0.00576 in.). Figure 10 is a plot of the Mach number as a function of the nozzle throat dimension for the nozzles used in this investigation. The nozzle throat height as accurate to within 0.0005 in., and was not more than 0.0065 in. From the graph, this corresponds to a Mach number of 5.75. However, the low Mach number, due to nozzle throat height error, was small compared with that resulting from large boundary layer growth.

Flow Quality

In Fig. 6 the optical clarity of the flow is quite good close to the channel centerline. Some deterioration appears within one to two inches from the nozzle trailing edge, and the wakes from each nozzle have excellent optical clarity at design Mach numbers. There are also, large wall boundary layers, which grow rapidly, suggesting boundary layer suction near the nozzles right improve the flow quality. Other inprovements in the flow quality can probably be accomplished

by better sealing of high-pressure leaks where the nozzles are butted against the steel mounting plates, and better alignment of the nozzles.

Diffuser Performance

Several different diffuser configurations were investigated to determine what diffuser throat area would start the cavity, generally, most arrangements started with a $A_d^*/A_t = 0.6$. Reproduced in Fig. 11 from Ref. 4:167 is a graph of the minimum swallowing throat area ratios versus diffuser entrance Mach numbers. There is good agreement with the theoretical curve, despite the presence of wakes in this multiple nozzle model.

After the flow was started in each test run the static pressure in the test section was 0.25 psia, and independent of the diffuser configuration used, provided a start condition was achieved. This static pressure would remain at 0.25 psia until the vacuum tank pressure increased to 2.5 psia. Supersonic flow lasted approximately 40 seconds and then a normal shock could be seen to move up toward the nozzles. Figure 12 depicts what this looks like.
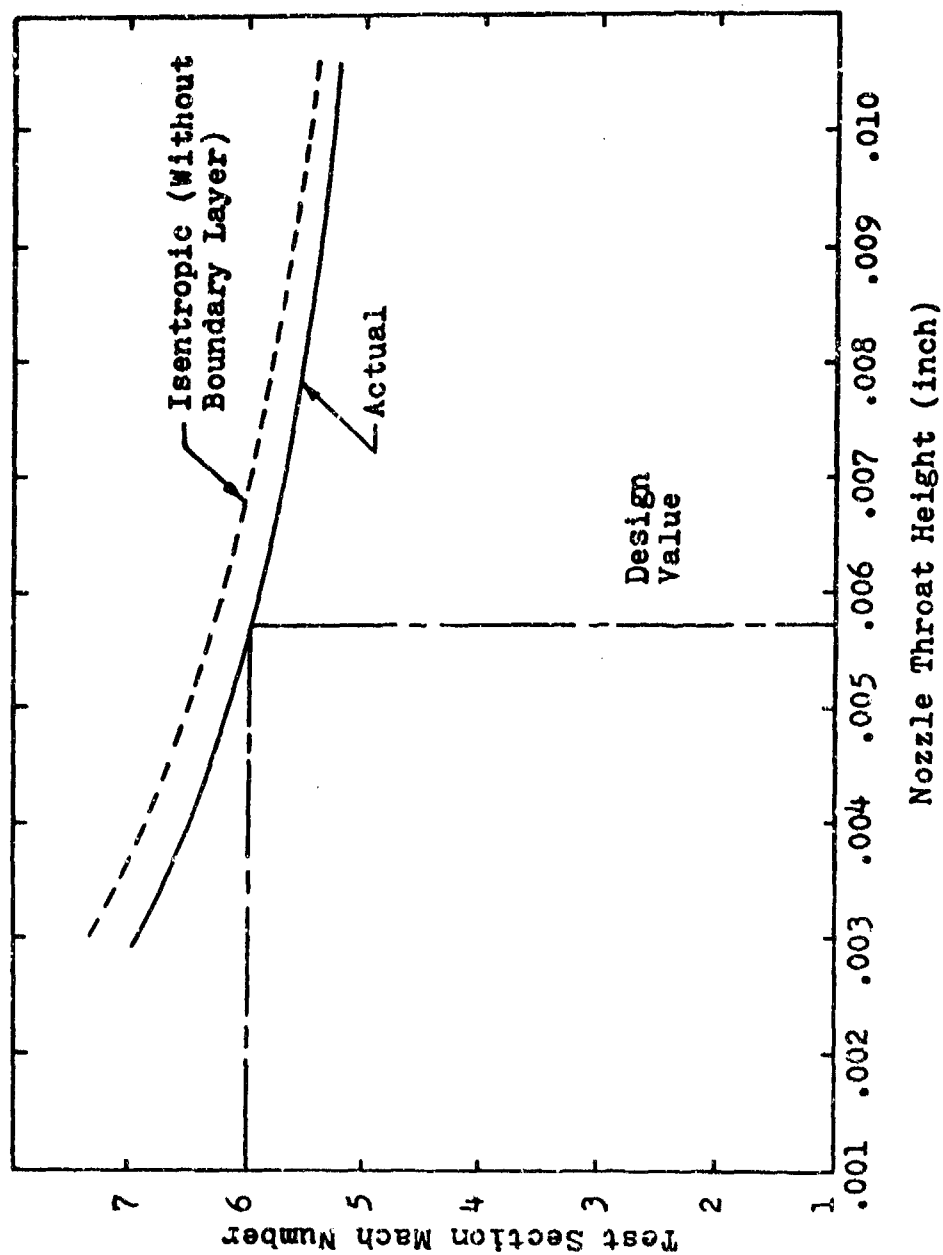
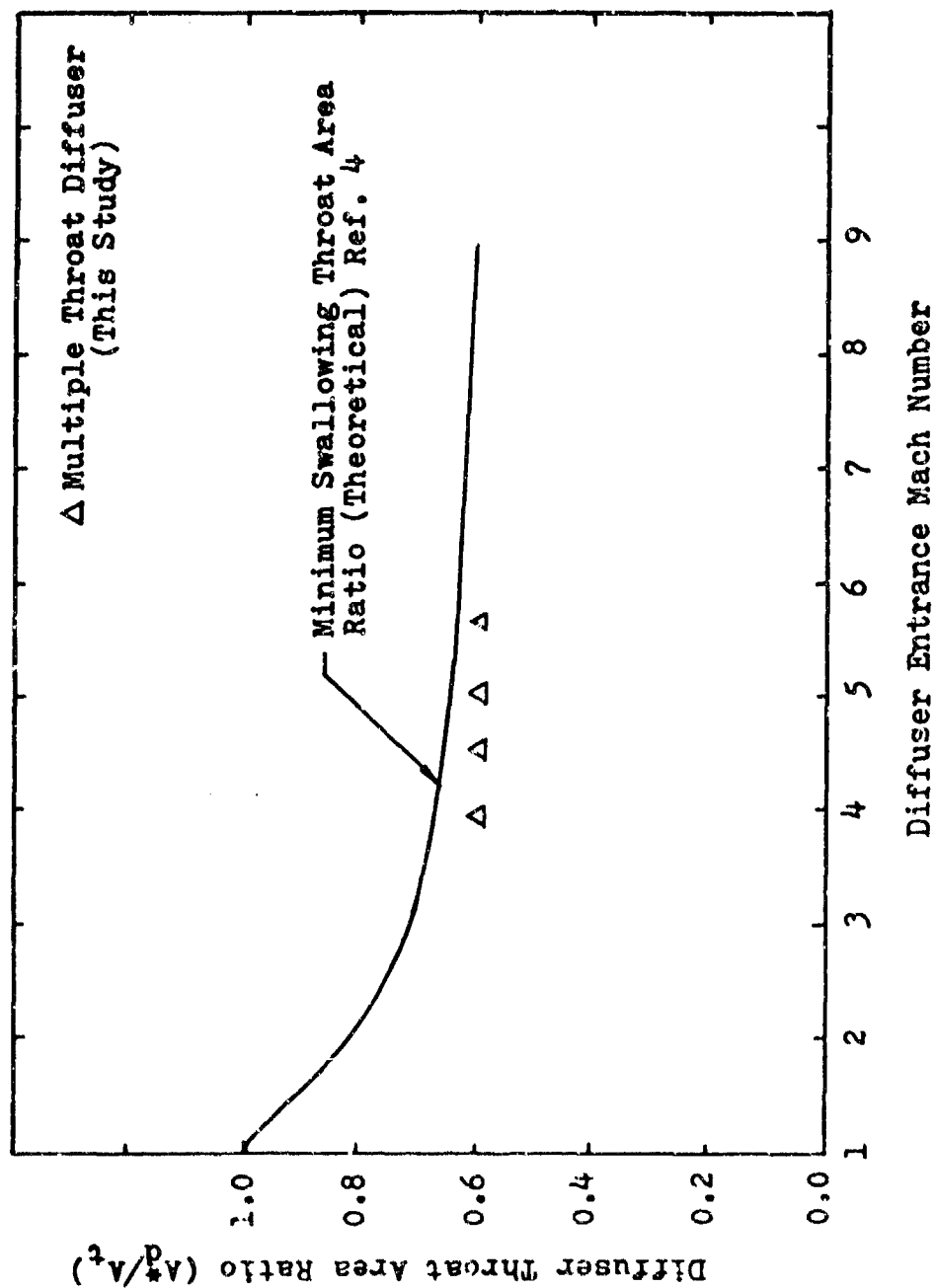Fig. 10. Effect of Error in Nozzle Throat Height on Exit Mach Number.

Fig. 11. Minimum Swallowing Throat Area Ratio for Diffuser versus Diffuser Entrance Mach Number (Ref. 4:167).
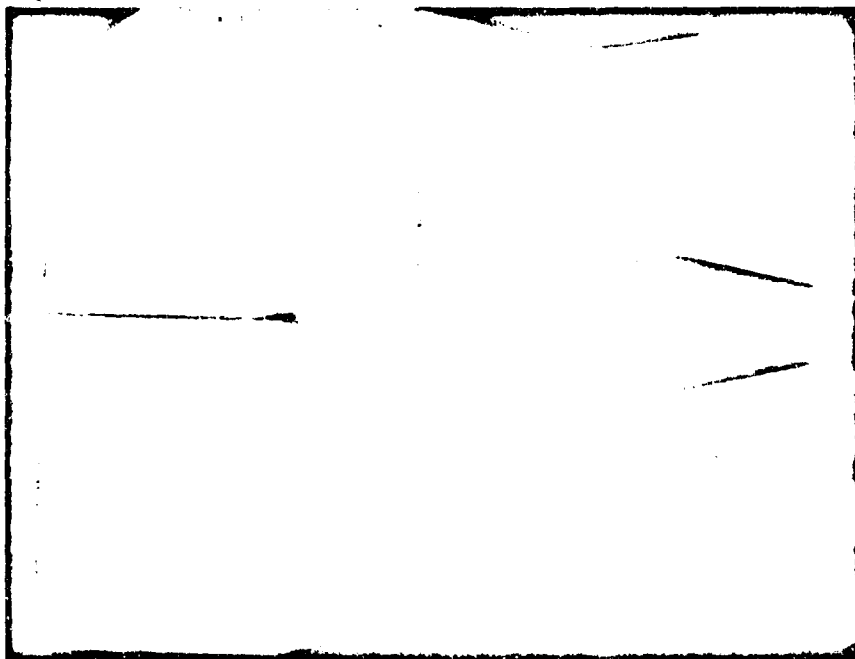
Fig. 12. Schlieren Photograph of Normal Shock Expulsion.

VI.   Conclusions and Recommendations

Conclusions

The optical clarity of the supersonic flow downstream from this multiple assembly was excellent. However, the optical clarity quickly deteriorates within one to two inches. Large wall boundary layers are present, limiting the high quality flow to near the channel centerline. The diffuser starting area ratio (A_d^*/A_t) is in close agreement with other studies even though in the double nozzle assembly there was a wake from each nozzle. Diffusers that worked best were those with symmetric geometry. A diffuser with no ramp along the wall as that of Fig. 3 was not effective. Multiple diffuser throats were efficient, making for a short diffuser design, provided each wedge had good symmetric design.

Recommendations

The multiple nozzle and multi-diffuser concept requires much more experimental testing to better understand the dynamic processes that occur. The following items should be investigated.

(1)   A determination of the influence on the design and performance of the diffuser using a wider flow channel with more nozzles to more accurately model GDL operation.

(2)   A study of variable geometry diffusers to determine if significant performance improvement results

as compared to the fixed geometry diffuser.

(3) A detailed pressure, velocity, Mach number, and total temperature distribution similar to that done in Ref. 7 should be done. In addition, increasing the total temperature in the stilling chamber would better model GDL operation.

(4) Flow disturbances such as vortices resulting from combustion initiation, effect the flow characteristics in the laser cavity. The flow characteristics may be also influenced by the nozzles vibrating at combustion initiation, changing the throat geometry. High speed movies of these dynamic changes would help to understand these processes.

(5) Design a boundary-layer suction capability into the channel walls near the nozzles as an effort to improve the flow characteristics near the walls.

Bibliography

1. Ames Aeronautical Laboratory Research Staff. *Equations, Tables, and Charts for Compressible Flow.* NACA Report 1135. 1953.

2. Chapman, Alan J. and William F. Walker. *Introductory Gas Dynamics.* Holt, Rinehart and Winston, Inc. New York. 1971.

3. Gerry, Edward T. "Gas Dynamic Lasers". *Laser Focus.* 6:27-31. December 1970.

4. Hermann, Dr. Rudoff. *Supersonic Inlet Diffusers and Introduction to Internal Aerodynamics.* Minneapolis-Honeywell Regulation Company. 1956.

5. Moore, John A. *Investigation of the Effect of Short Fixed Diffusers on Starting Blow Down Jets in the Mach Number Range from 2.7 to 4.5.* Langley Aeronautical Laboratory. Langley Field Va. NACA. Washington. January 1956. Technical Note 3545.

6. Neumann, E. P. and F. Lustwerk. "Supersonic Diffusers for Wind Tunnels". *Journal of Applied Mechanics.* June 1949.

7. Wagner, Jerry L. *A Cold Flowfield Experimental Study Associated with a Two-Dimensional Multiple Nozzle.* Naval Ordance Laboratory, White Oak, Silver Springs, Maryland. NOLTR 71-78, AD-731677.

Vita

David G. Clawson was born on 16 January 1948, in Logan, Utah. He is the son of Otto Grant and Pauline L. Clawson. After graduating from Sky View High School, Smithfield, Utah in June 1966, he entered Utah State University and also enrolled in the Air Force ROTC program at USU in 1969. In July 1972, he graduated from USU with a Bachelor of Science Degree in Mechanical Engineering and was commissioned as Second Lieutenant in the USAF. In August 1972, he entered active duty and was assigned to the Air Force Institute of Technology for Graduate Study in Aerospace Engineering. His assignment upon completion of the AFIT program is at Norton AFB in the Space/Missle Systems, Det. AKOO.

    Permanent Address: 2800 W. 800 So.
                          Lewiston, Utah 84320

This thesis was typed by Mrs. Muriel Pearce.